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We report the initial results of a multiple detector search for short bursts of gravitational radiation, covering 1997 and 1998 with data from a network of five cryogenic resonant detectors. This is the first significant search with more than two detectors observing simultaneously. A false alarm rate lower than 1 per 10^4 years has been achieved when three or more detectors were operating simultaneously. The typical threshold was $H \simeq 4 \times 10^{-21} Hz^{-1}$ on the Fourier component of the gravitational wave strain amplitude. New upper limits on amplitude and rate of g.w. bursts have been set.

95.85.Sz, 04.80.Nm, 95.45.+i

The direct detection of gravitational waves will be a watershed event for both the physics of gravitation and the investigation of compact astronomical objects. A variety of astrophysical events are expected to produce gravitational waves of short duration ($\ll$ 1 sec), or *gw bursts*, such as the gravitational collapse of stars or the final few orbits and the subsequent coalescence of a close binary system of neutron stars or black holes [1]. Due to the inherent weakness of such signals, and the difficulty in distinguishing them from a myriad of noise sources, the direct detection of a gw burst will require coincident detection by multiple detectors with uncorrelated noise. Searches for gw bursts over periods of observation of $1-3$ months have been performed in the past by pairs of cryogenic resonant bar detectors [2–4], setting upper limits on the incoming rate. A few days of observation have been reported for simultaneous operation of three cryogenic bar detectors [2] and, with much less sensitivity, of a pair of short-arm interferometric detectors [5]. Upper limits on gw signals from coalescing binaries has been recently reported also by a single interferometric detector for 25 hours of observation [6].

In the last few years, the increase of the number of cryogenic resonant detectors in simultaneous operation has greatly improved the prospects of obtaining a confident detection of gw bursts. There are now five operational cryogenic bar detectors: *ALLEGRO* (Baton Rouge, Louisiana, USA) [7], *AURIGA* (Legnaro, Italy) [8], *EXPLORER* (CERN) [9], *NAUTILUS* (Frascati, Italy) [10] and *NIOBE* (Perth, Australia) [11]. The groups operating these detectors agreed in 1997 to start a global search for short ($\sim 1\ ms$) gw bursts under common protocols, by establishing the International Gravitational Event Collaboration (*IGEC*) [12].

All these detectors basically use the same principle of operation. The gw excites the first longitudinal mode of the cylindrical bar, which is cooled to cryogenic temperatures to reduce the thermal noise and is isolated from seismic and acoustic disturbances. To measure the strain of the bar, a secondary mechanical resonator tuned to the cited mode is mounted on one bar face and a sensor measures the displacement between the secondary resonator and the bar face. The resulting noise in terms of strain is $5 - 10 \times 10^{-22}/\sqrt{\mathrm{Hz}}$ in an bandwidth of $\sim 1\ Hz$ surrounding the two coupled-mode frequencies. Some of the important physical parameters of the five detectors are shown in Table 1. The axes of all the bar detectors are aligned to within a few degrees of one another, so that the chance of coincidence detection is maximised. The common orientation makes the amplitude acceptance [13] of the detectors for the Galactic Center direction greater than 0.7 for about 60% of the time.

Each detector output is processed by filters optimized for short bursts, giving the estimate for the Fourier component H of the gw strain amplitude $h(t)$ in the detection bandwidth. With the exception of the *ALLEGRO* detector, the noise of the detectors was typically not stationary over long observation times and was affected by some unmodeled noise sources, whose correlation with common environmental noise sources was found to be weak [16]. Fig. 1 shows for each detector the variability of the Fourier component of the gw corresponding to unity signal-to-noise ratio, H_{rms}, during 1997-1998. The detectors had quite close noise levels, since the typical values of H_{rms} were all within a factor of 3. The corresponding amplitude of the metric perturbation can be computed assuming a model for the burst shape: for a conventional (flat spectrum) $\sim 10^{-3}s$ burst, the Fourier component H should be multiplied by $\sim 10^3 Hz$ to get the strain amplitude h.

We point out that this search for bursts, or δ-*like* signals, is suitable for any transient gw which shows a nearly flat Fourier transform $H(\omega)$ of its amplitude $h(t)$ at the two resonant frequencies of each detector. The metric perturbation $h(t)$ can either be a millisecond pulse, a signal made by a few millisecond cycles or a signal sweeping in frequency through the detector resonances. The IGEC search is therefore sensitive to different kinds of gw sources such as a stellar gravitational collapse [1], the last stable orbits of an inspiralling NS or BH binary, its merging and its final ringdown [15].

This letter reports the results of the first coincidence search for gw bursts performed by the IGEC observatory. The observations covered most of $1997-1998$, including 625.0 days with at least one detector in operation, 260.4 days with at least two detectors in simultaneous operation, 89.7 days with three detectors, and 15.5 days with four. This is the first search with significant observation time with more than two detectors. It would have been much greater if it had been possible to operate all of these very delicate instruments with higher duty factors than the $\sim 50\%$ typical during this period. More details on the observatory, its data exchange protocol and the exchanged data set can be found in Ref. [14].

The analysis of the data can be divided into two parts: generation of candidate *event lists* for each of the individual detectors, and coincidence analysis using the lists.

Each IGEC group extracted the candidates for gw bursts, or *events*, by applying a threshold to the filtered output of the detector. The events were described by their Fourier magnitude, their arrival time, the detector noise at that time and other auxiliary information. To limit the expected rate of accidental coincidences, each detector threshold was adaptively set to obtain a maximum event rate of ~ 100 / day, with typical values in the range $H_{det} \sim 2-6\times 10^{-21} Hz^{-1}$ corresponding to magnitude signal-to-noise ratio SNR $\simeq 3-5$. Single spurious excitations are vetoed against disturbances detected by environmental sensors. The *AURIGA* detector checked each event against the expected waveform template by means of a χ^2 test [17]. The lists of the events exchanged within IGEC by each detector also include declarations of the off- and on- times for the detectors.

All searches for coincident events used a time window of 1.0 second. This choice limits the false dismissal probability to less than a few per cent while it ensures a very low false alarm probability when at least three detectors are observing simultaneously. No three- and four-fold coincidence was detected, and therefore we did not identify candidates for gravitational wave detection in the 89.7 *days* of three-fold observation. The detector thresholds were typically $3\times 10^{-21} Hz^{-1}$ for the most sensitive three-fold configuration (*ALLEGRO-AURIGA-NAUTILUS*) and $5\times 10^{-21} Hz^{-1}$ for the others, corresponding to respectively ~ 0.04 and 0.11 $M_\odot$ converted in an optimally polarized g.w. burst of 1 ms duration at the distance of the Galactic Center (10 kPc), assuming that the source is emitting isotropically [18]. For comparison, the signal expected from the last stable orbits of an optimally oriented NS coalescing binary at 10 kPc with $2\times 1.4\ M_\odot$, would give $H = 3-4\times 10^{-21} Hz^{-1}$ at the detector resonant frequencies. The number and amplitude of the two-fold coincidences found in the 260.4 *days* of two-fold observation are in agreement with the estimated accidental background [14].

The estimation of the false alarm rate is a crucial element in any gw search. It allows for the interpretation of any observed coincidences as well as the evaluation of the potential of the observatory. Since the events arrival times of each detector are randomly distributed with a non stationary rate, the expected background of accidental coincidences can be computed by two methods: i) by modeling the event times as Poisson point process and using the measured rates of events for each detector, and ii) by counting the coincidences after performing even time shifts of the event times of one detector with respect to the others [19].

In the first approach, the expected rate of accidental coincidences is [20]

$$\lambda = N \frac{(\Delta t)^{N-1}}{T_{obs}^N} \prod_{i=1}^{N} n_i, \tag{0.1}$$

where N is the number of detectors simultaneously operating, T_{obs} their common observation time, $\Delta t = 1\ s$ the maximum time separation for a coincidence, n_i the number of events of the ith detector during T_{obs}. This equation holds even if the event rates of detectors are not stationary as long as they are uncorrelated among different detectors.

The second method used to estimate the false alarm rate of coincidences is more empirical. In the case of the two-fold coincidence searches, these results are in agreement with those predicted through Eq. 0.1 [14], and demonstrate in addition that the event rates of different detectors are uncorrelated.

The capabilities of the IGEC observatory with respect to the false alarm probability are shown in Fig. 2 for a few sample configurations of the observatory. The accidental rate is calculated as a function of a signal amplitude threshold H_{thr} at the detectors by applying Eq. 0.1 to the number of events of the detectors whose amplitude is $\geq H_{thr}$. The typical time variability of the istantaneous accidental rate λ has been calculated by means of a Monte Carlo simulation based on the past behaviour of event rates on single detectors. It turned out to be about one order of magnitude with respect to the mean and is mainly determined by the non stationary performances of the detectors. The estimated mean background of two-fold coincidences is still fairly high, unless H_{thr} is raised well above the data exchange threshold H_{det}.

On the other hand, a three-fold or four-fold coincidence search mantains a high statistical significance even for $H_{thr} \sim H_{det}$, since the expected accidental rates are low enough: respectively less than 1 false alarm per 10^4 or 10^6 *years* of observation at $H_{thr} \sim 4 \times 10^{-21} Hz^{-1}$, falling rapidly as H_{thr} increases. In fact, the IGEC accidental background noise would remain negligible even after centuries of observation time.

The 260 *days* of observation with two or more detectors in simultaneous operation improved by about a factor of three the previously set upper limit on the rate of gw bursts incident on the Earth [3]. Assuming the emission is described by a stationary Poisson point process and using the same procedure as in Ref. [2,3], the limiting rate set for a gw burst emission with 95% confidence is $\leq 4\ year^{-1}$ for $H_{gw} \geq 10^{-20} Hz^{-1}$, and $\leq 12\ year^{-1}$ for $H_{gw} \geq 6 \times 10^{-21} Hz^{-1}$ (Fig. 2). A complete analysis is in progress.

The IGEC observatory can also set an upper limit on the amplitude of single gw burst corresponding to an astronomical trigger, which can be defined within a few hours, as for a supernova, or some seconds, as for a gamma ray burst. For time windows of the order of the hour or larger, each detector is likely to show accidental events and therefore this upper limit benefits from a multiple coincidence search among the operating detectors.

A sample of the upper limits on the amplitude of gw bursts, within a time span of 1 *hour* (optimal polarization and orientation), are shown in Fig. 3 for a few weeks of 1998, when up to four detectors were operating. This limit has been calculated by considering hour by hour the gw burst excitation which ensures a 95% confidence of detection. To specialize this upper limit for a specific source direction, each detector response should be divided by its antenna pattern. In 1998, the IGEC observatory ensured a satisfactory coverage of 94% and 21% of the year with an upper limit better than $H_{gw} = 6$ and $4 \times 10^{-21} Hz^{-1}$ respectively ($h_{gw} \sim 6$ and 4×10^{-18} for a $\sim 10^{-3} s$ burst). For a source at the Galactic Center emitting isotropically [18], these upper limits correspond to about 0.16 and 0.07 $M_\odot$ converted in gw burst in the optimal polarization. The corresponding observation times of the Galactic Center by IGEC at these sensitivities have been respectively 44% and 7.5% of 1998.

Finally, we remark that the IGEC observatory is capable of monitoring the strongest galactic sources with a very low false alarm probability when at least three detectors are simultaneously operating. In particular, for stellar core gravitational collapses the IGEC observatory has comparable capabilities to those of the network of the operating neutrino detectors [21].

All the groups involved are actively working for upgrading the current detector performances and therefore we expect in the near future to extend the observation range to the Local Group of galaxies, which means an increase of a factor of 10 of the observed mass.

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[1] B.F. Schutz, Class. Quant. Grav. 16 (1999) A131.
[2] E. Amaldi et al., Astron. Astrophys. 216 (1989) 325.
[3] P. Astone et al., Phys. Rev. D 59 (1999) 122001.
[4] P. Astone et al., Astroparticle Phys. 10 (1999) 83.
[5] D. Nicholson et al., Phys. Lett. A 218, 175 (1996)
[6] B. Allen et al., Phys. Rev. Lett. 83, 1498 (1999)
[7] E. Mauceli et al., Phys. Rev. D 54 (1997) 1264.
[8] G.A. Prodi et al., in Proc. of the Second Edoardo Amaldi Conference, ed. E. Coccia et al. (World Scientific, Singapore, 1998) pp. 148-158.
[9] P. Astone et al., Phys. Rev. D 47 (1993) 362; from 1998 Explorer is a CERN Recognized Experiment.
[10] P. Astone et al., Astroparticle Phys. 7 (1997) 231.
[11] D.G. Blair et al., Phys. Rev. Lett. 74 (1995) 1908.
[12] see for instance: http://igec.lnl.infn.it
[13] a bar detector detects the fraction $sin^2(\theta)$ of the amplitude of an incident gw with optimal polarization, where θ is the angle between the bar axis and the gw direction.
[14] G.A. Prodi et al., Int. J. Mod. Phys. D (2000), in press
[15] E.E. Flanagan, S. A. Hughes, Phys. Rev. D 57 (1998) 4535.
[16] I.S. Heng et al., Phys. Lett. A 218 (1995) 190.

[17] L. Baggio et al., Phys. Rev. D 61 (2000) 102001.
[18] see for instance: M. Cerdonio et al., in Proc. GR15 Conf., eds. N. Dadhich and J. Narlikar, (IUCAA, India, 1998) p.211.
[19] J. Weber, Phys. Rev. Lett. (1969) 1320.
[20] see for instance: R.K.Bock et al., in Data analysis techniques for high-energy physics experiments, Cambridge University (1990) p. 22.
[21] see for instance: K. Scholberg, in Proc. of the Third Edoardo Amaldi Conference, ed. S. Meshkov et al. (A.I.P., 2000) in press

TABLE I. Main characteristics of the five resonant cryogenic bar detectors. The average Fourier component of the gw in the detection bandwidth is related to some listed parameters by $H = (4L\nu^2)^{-1}\sqrt{E/M}$, where E is the energy deposited in the bar by the gw and ν is the mean of the mode frequencies. The bars are made by Al5056 except for NIOBE, whose bar is made of Nb. The sub-kelvin detectors and NIOBE showed very similar typical energy sensitivity in 1997-1998, better of a factor of about 4 with respect to the other detectors. The differences in mass and material, though, affect the gw sensitivity and give a conversion factor from $\sqrt{E}$ to H which is 2.3 times worse for NIOBE than for the other detectors.

detector	ALLEGRO	AURIGA	EXPLORER	NAUTILUS	NIOBE
Mode frequencies $[Hz]$	895, 920	912, 930	905, 921	908, 924	694, 713
Bar mass M $[kg]$	2296	2230	2270	2260	1500
Bar length L $[m]$	3.0	2.9	3.0	3.0	2.75
Bar temperature $[K]$	4.2	0.2	2.6	0.1	5.0
Longitude	$91^\circ 10' 44" W$	$11^\circ 56' 54" E$	$6^\circ 12' E$	$12^\circ 40' 21" E$	$115^\circ 49' E$
Latitude	$30^\circ 27' 45" N$	$45^\circ 21' 12" N$	$46^\circ 27' N$	$41^\circ 49' 26" N$	$31^\circ 56' S$
Azimuth	$40^\circ W$	$44^\circ E$	$39^\circ E$	$44^\circ E$	0°

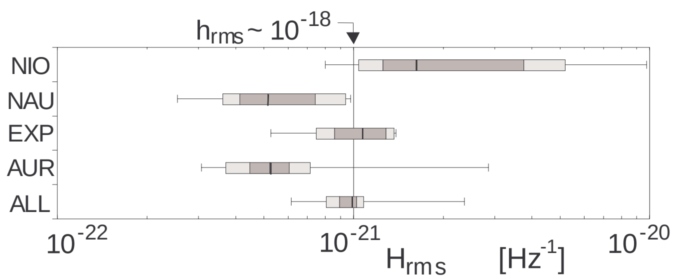

FIG. 1. Spread of the mean noise of detectors during 1997-1998 in terms of the Fourier component H_{rms} of the gw at $SNR = 1$ plotted by some selected fractions of observation time for which the sensitivity has been better than H_{rms}: bold tic 50%, gray band $16 - 84\%$, white band $2.5 - 97.5\%$, "T" lines $0 - 100\%$. The corresponding gw amplitude h_{rms} for a $\sim 10^{-3}s$ burst is sketched in the upper scale.

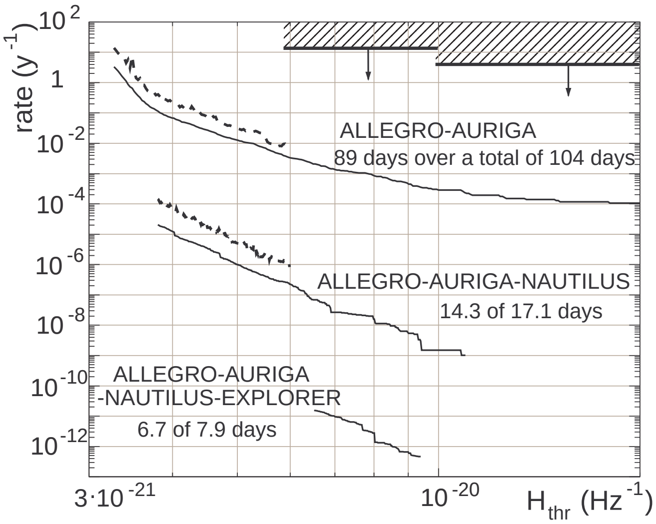

FIG. 2. Estimated rate of accidental coincidences, λ $[year^{-1}]$, versus the threshold H_{thr} $[Hz^{-1}]$ for a sample pair, triple and four-tuple of detectors in 1997- 1998. The continuos lines show the mean value of λ for signal amplitudes $\geq H_{thr}$. The dotted lines represent the one *std. dev.* upper bounds for the time variation of the istantaneous accidental rates. This figure takes into account the best 85% of common observation times, when every detector had an event search threshold lower than 3.25, 3.8 and 6.5 $\times 10^{-21} Hz^{-1}$, respectively for the pair, the triple and the four-tuple. The λ for the other operative configurations of detectors were similar, allowing for a small increase of the corresponding H_{thr}, at most by a factor of 2. The two bold horizontal lines with arrows stand for the new upper limit set by all IGEC detectors on the rate of incoming gw bursts during 1997-1998.

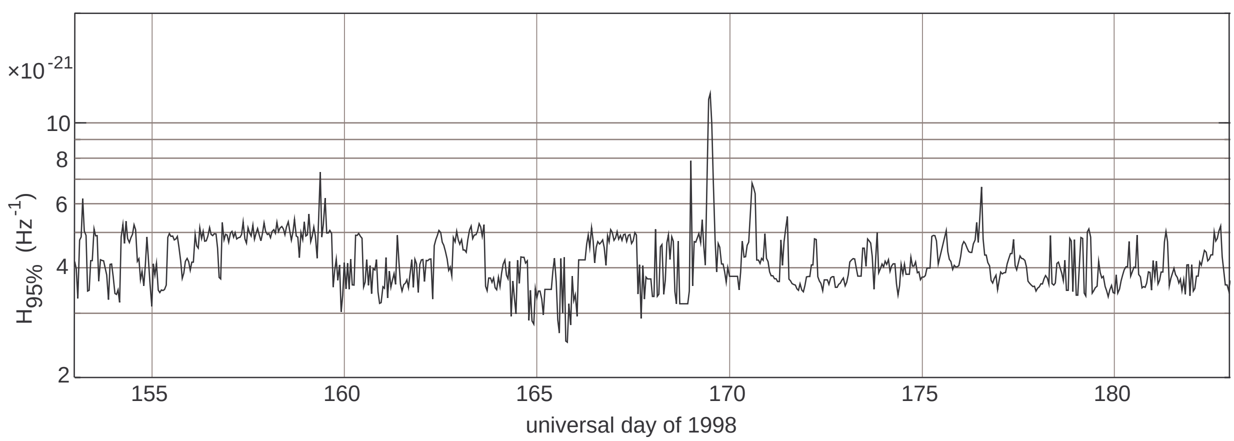

FIG. 3. A sample of the upper limit with 95% confidence on the amplitude of single gw bursts incident with optimal polarization and orientation on the IGEC observatory hour by hour in June 1998.